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Short Term Memory for Tempo in a Motor Timing Experiment

Sari Hooper
University of Rhode Island

SHORT TERM MEMORY FOR TEMPO IN A MOTOR TIMING EXPERIMENT

BY

SARI HOOPER

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Abstract

This study investigated the role of short term memory in the motor reproduction of tempo. Seven undergraduate students participated in a finger-tapping experiment, in which retention intervals were incorporated into the classic continuation tapping paradigm. A two-way within-subjects design was employed, where subjects listen to and then attempt to reproduce a set tempo at 25 sub-second levels after retention intervals of 5 or 25 seconds. Musical Instrument Digital Interface (MIDI) software (Collyer, Boatright-Horowitz, & Hooper, 1997) was used to present stimulus tempos and record subjects tapping. Analyses of the inter-response intervals (IRIs) indicated an effect of retention interval on the form of the oscillator signature (Collyer, Broadbent, & Church, 1992; 1994), the nonlinear component of temporal reproduction in continuation tapping. Of three current approaches to interval timing that were reviewed, a 'natural' time period account appeared most promising as an explanation for the retention interval effect. This account would attribute the effect to a relaxation of IRI toward a natural period of 550 - 575 ms (corresponding to a frequency just below 2 Hz).

Acknowledgment

I would like to dedicate this work to my father

Glenn V. Wahlin

April 25, 1922 - October 9, 1998

Special thanks to my major professor and advisor, Charles Collyer. His extensive knowledge and understanding have always provided answers to my questions and direction for my goals. I would also like to extend special thanks to my dear friend and supportive lab partner, Arthur Little.

I am fortunate to have a wonderful family and good friends. My husband, David, and my children, Robert and Britta, have provided endless patience and compassion. My close friends, Lynn Skugrud and Scott Miller, have been a source of strength and encouragement --- Thank you.

Table of Contents

List of Tables

List of Figures

The internal mechanisms that allow animals and humans to keep track of time and form representations of time intervals in memory have been a subject of inquiry for years. The concept of a 'biological clock' has been suggested as an endogenous mechanism for time perception. The clock concept has been used to understand such timing phenomena as migration, stages of development, and the sleep cycle. Studies have shown that animals possess any number of internal free-running rhythms or oscillations that demonstrate periodicity (Gallistel, 1990). The most widely studied self-sustaining oscillator has been the twenty-four hour circadian rhythm. The circadian rhythm and other biological oscillations are regulated by external stimuli from the environment. For example, the environmental cycles of light are considered to be a regulator for land animals, as are the tides for marine animals. A stimulus in the environment that influences a free-running oscillator is referred to as a zeitgeber. Synchronization occurs between the internal oscillations and the external zeitgeber regulating behavior; without it the endogenous oscillations would be free to drift out of phase with 'real' time. Investigators as early as Darwin have encountered numerous examples to support the existence of internal timekeeping mechanisms (Darwin, 1845; cited in Gallistel, 1990), but just how time is represented in the memory of an organism remains uncertain.

Most experiments involving the phenomena of time perception can be divided into two general categories of investigation: studies that have looked at interval timing -- the ability to estimate the duration of a time interval, and those that have investigated periodic timing -- the ability to record time of occurrence relative to a clock, calendar, or other frame of temporal reference. Investigations of time perception and temporal phenomena have appeared in different areas of the research literature, including music and speech, animal interval and periodic responding experiments, and human motor timing and duration discrimination.

Experiments of interval timing, using repetitive finger-tapping tasks, have found that people are capable of accurately perceiving tempo (beats per minute) and reproducing short intervals of time (less than one second). Experimentation in human timing that employs the finger tapping procedure distinguishes between two kinds of tasks, synchronization and continuation. In synchronization tapping a subject is asked to tap along with a pacer stimulus (e.g. metronome-like series of tones) at a given tempo. Continuation tapping involves first listening to the pacer stimulus, then attempting to reproduce the tempo heard without the aid of the tones. For these types of tasks, an interstimulus interval (ISI) refers to the presented interval of time between the stimulus sounds to which a subject listens. The time between the taps that the subject produces is referred to as the interresponse interval (IRI) and has been the data of interest. In a task where subjects use finger-tapping to reproduce short time intervals (ranging from 175 to 1000 ms), it has been found that the ISI can account for about 99% of the variance because IRI approximates ISI with great accuracy.

However, there are some ISI values which are consistently reproduced a little too fast and others that are consistently reproduced a little too slow. These small systematic deviations in timing, reported by Collyer, Broadbent, & Church (1992; 1994), and recently confirmed by Collyer, Boatright-Horowitz, & Hooper (1997) together make up a nonlinear function that has been referred to as the oscillator signature. More specifically, the oscillator signature is a function relating (IRI / ISI x 100) to ISI; its graphical appearance, shown in Figure 1, is wavelike with peaks and valleys that depart significantly from zero, but only by a few percentage points. It can be thought of as a representation of the way in which IRI departs from the identity function, IRI = ISI.

It has been proposed (Collyer, Broadbent, & Church 1992; 1994) that the existence of these systematic errors in time reproduction provide important clues about the endogenous timing mechanisms that allow us to differentiate durations of time and reproduce time intervals as well as we do. The nonlinearity of an oscillator signature may be interpreted as a way in which time intervals are initially represented or encoded internally, but an alternative or possibly additional source of nonlinearity, that has yet to be explored in human tapping, is memory.

Memory and the Information-Processing Approach

For years, researchers and psychologists have been investigating memory, how it is initially created and encoded, and how it is processed, stored, and retrieved. The early experiments on memory allowed investigators to draw conclusions about the duration and capacity of separate memory structures. From an information-processing approach, memory has been described as a system of separate but interlocking storages. In this approach, three basic types of memory have been identified; sensory storage, short term memory, and long term storage.

Sensory memory storage is brief, lasting less than a few seconds, and its capacity is thought to be quite large. The sensory register automatically encodes incoming stimuli from the senses, where it will quickly decay unless it is allocated for transfer into a more durable storage. Many early sensory register experiments were performed using visual stimuli. Experiments conducted by Sperling in the 1960's found that up to four elements, such as letters, presented visually for 50 ms were stored for up to 300 ms before decaying. Auditory stimuli, however, are believed to be held in sensory storage up to ten times longer (Best, 1995). In long term memory storage, on the other hand, the duration of memories is believed to be permanent, at least potentially. Long term storage and retrieval of information are subject to various types of distortion, decay, and interference. The capacity of long term storage is not known to be limited.

Short term memory, or what is sometimes referred to as working memory, is more durable than the sensory register, but not permanent like long term storage, and its capacity is limited. Short term memory can store as many as seven items, such as words, for about thirty seconds. Early short term memory and retention interval studies (Peterson & Peterson, 1959; Atkinson & Shiffrin, 1968) have shown that if rehearsal is allowed, information can be retained for more than thirty seconds. If rehearsal is prevented, by the use of a distracter task, information held in short term memory seems to be lost by about eighteen seconds. As long as the information is continually being worked on, or refreshed by rehearsal, it can reside in short term memory for longer periods of time or perhaps be transferred to long term memory storage.

Using an information-processing approach to memory has advantages. It makes a distinction between the structural components of memory, making it convenient to differentiate and communicate, providing an interpretation for how information is processed and may flow through the memory system in serial manner. It provides a conventional structure to which a model for timing has been applied (Church & Broadbent, 1990). A flow diagram of a general information-processing model of memory, shown in Figure 2, portrays the mind as a information processing machine with interconnections of input, processing, and output. Stimuli from the environment (input) enter at the sensory register, are processed, and then a decision and motor response is produced (output). The information-processing model for timing, also shown in Figure 2, resembles the structure of the general model, but the components have been altered to address the way in which the perception of time may occur. The model proposes how elapsed intervals of time might be processed and compared in memory. The pacemaker and the accumulator represent a clock-like mechanism, with the pacemaker designating the rate at which ticks or beats are occurring, and the accumulator counting or summing up the number of ticks. The reference memory holds remembered intervals of time to which the current value in the accumulator is compared. When the value of the accumulator approximates the reference memory value, indicating time is up, a decision is made.

The information-processing diagram represents the most conventional interpretation of scalar timing theory (Gibbon, Church, & Meck, 1984; Gibbon, 1991) which assumes that measurement of elapsed time can be expressed as the comparison of a current count to a remembered value. Scalar timing theory initially addressed animal interval timing experiments. These experiments used a variation of fixed interval operant conditioning in which a signal (noise or light) initiates the beginning of a trial, then at a given fixed interval of time, on some trials but not on others, a reward (food) becomes available when the animal responds. The unrewarded trials, where the animal's rate of responding rises to a peak and then declines as time continues to elapse after the trained interval, provide the data of interest. Findings from experiments employing this 'peak' procedure have indicated that a scalar parameter relates the current experienced duration of the elapsed interval in the working memory to the internal remembered duration of the interval in the reference memory using a ratio comparison.

The information-processing version of scalar timing theory provides a good representation of how animals may process intervals of time. However, it can not adequately address how humans can perceive and reproduce time intervals in a finger tapping task. The single oscillator model can account for the approximately linear relationship between the IRIs and ISIs, but can not explain the nonlinear oscillator signature finding.

The Multiple Oscillator Connectionist Model

The connectionist model of timing was developed by researchers at Brown University (Church & Broadbent, 1990; 1991) and is an elaboration on the original information-processing version of scalar timing theory. The connectionist version, illustrated in both a familiar and a more complex form in Figure 3, is a multiple-oscillator model. It differs from the information-processing timing model in that it can be directly applied to the human tapping task and is able to simulate the systematic residuals that define an oscillator signature (Collyer & Church, 1998). In the connectionist version, the pacemaker has been replaced with a set of oscillators each having its own period of oscillation. These are connected to the elements referred to as status indicators. The oscillators and status indicators are represented as vectors. In Figure 3, the operations of storage in working memory and retrieval are shown separately. The nonlinear encoding of time occurs because of limited precision. Vector elements represent only the half phases of the oscillators which are recorded as 0's or 1's (0 = first half ; 1= second half). This encoding method produces a representation of time that is a categorical step-like approximation to real time, and resembles a rounding-error function (Collyer, Broadbent, & Church, 1994). The working memory is an auto-association matrix consisting of the outer product of the storage vector with its transpose. The reference memory which contains the remembered information, is also represented as a matrix, and the decision to respond is determined by a thresholded comparison based on the similarity of current time to remembered time.

The connectionist model is one approach to timing which allows for nonlinearity, but there are other theories of how time may be perceived and reproduced that also may offer potential explanations for the oscillator signature finding. Two such theories are the broadcast theory of timing and 'natural' time periods.

The Broadcast Theory of Timing

The broadcast theory of timing (Rosenbaum, 1998) provides a different explanation for the source of the systematic deviations found in timing experiments. It proposes a common physiological mechanism for both perceived encoding of intervals and the production of the intervals, based on the rhythmic properties of neural processes. The ability to perceive and produce intervals of time is explained by the distance and speed for signals to travel neural fibers and connections. Timing is considered to be regulated by a neural connection between two neural elements having a desired length of delay that has been formed through trial and error learning. When applying the theory to the nonlinearity found in human tapping experiments, the explanation is based on how rapidly variance accumulates as a time interval increases. For example, when an ISI is too long, with too much variability occurring, subdivision of the interval may become an attractive alternative in order to decrease variability. By subdividing intervals (Parzen, 1960) they can be represented as the sums of shorter intervals; $D = d_1 + d_2$. Potentially, the variance can be reduced because of the property; $Var(D) > var(d_1) + var(d_2)$. If minimizing variance is desired when producing the longer, more highly variable time intervals, a subject may decide to be inaccurate in order to reduce the variability. In turn, if there are time intervals in which subdivision is advantageous, there would also be certain time intervals having relatively low variance. The pattern of data produced from this theoretical reasoning would roughly approximate the data found in tapping experiments, providing a possible source for the oscillator signature finding. In other words, for the broadcast theory, an individual's oscillator signature may come from preferring precision in performance over accuracy.

'Natural' Time Periods - Underlying Oscillators

It has been proposed by Collyer et al. (1992; 1994) that the origin of the oscillator signature may be an internal timing mechanism operating with multiple oscillators at several 'natural' time periods. Like the endogenous circadian rhythm that has a natural period lasting about a day, additional underlying oscillators operating at natural periods in the sub-second range may be responsible for the nonlinearity found in human tapping. Although these biological rhythms are seen as somewhat stable with natural periodic oscillations, they can be continually modified or reset by the external cycles or zeitgeber in the environment. This process, referred to as entrainment, allows the free-running internal oscillation to remain in synchrony with the external oscillations. The natural time periods at which multiple oscillatory processes are occurring therefore have some degree of adjustibility. The sense in which a period is 'natural' is that the oscillator may maintain some degree of resistance to entrainment at other rates. This resistance may produce the systematic deviations found in continuation tapping when the pacer stimulus is no longer present. As suggested by Collyer et al. (1992; 1994), the negative-going zero crossings of the residuals at 250 ms and 541 ms may provide an estimate of 'natural' periods in the timing system.

The experiment presented here was an extension of the existing time perception findings, which so far have not explicitly addressed the role of memory. It is the first to study the role of short term memory for the reproduction of specified tempos in a finger-tapping task. The component of short term memory was added to the classic continuation tapping experiment (Collyer et al. 1992; 1994; 1997) by incorporating retention intervals of 5 and 25 seconds between the perception and reproduction phases of the task. As with previous experiments using a finger-tapping task, the subject first listened to a specified tempo, but unlike the previous experiments, the subject did not synchronize with the tones and continue tapping. Instead he or she listened to a tempo, holding the tempo in memory without actual tapping. After a given interval of time, the subject began tapping and attempted to reproduce the tempo held in memory. In the present experiment, the independent variables were the ISIs (ranging from 200 to 800 ms, in 25 ms steps) and the retention intervals (5 and 25 seconds). The dependent measures were the median IRIs and the semi-interquartile range (SIQR) of the IRIs at the trial level, and means of these measures over the trials run under each condition. It was hypothesized that by introducing short term memory during a retention interval between the stimulus sounds, which define the ISI, and the beginning of the subject's tapping, there would be opportunity for the subject's memory representation of an ISI to be distorted due to the structure of the endogenous mechanisms involved in timing. The theories and models of timing that have been considered in this paper generate different expectations as to the influence that the memory component may have.

According to the multiple oscillator connectionist model, time is initially encoded nonlinearly by a vector of oscillators. The "rounding" errors that produce the oscillator signature are accounted for at the initial encoding phase of the task. Because the encoding phase, when the subject listens to the tempo, is presented the same for the 5 and 25 second retention interval conditions of the experiment, the oscillator signatures produced by the two conditions should be similar and also comparable to the previously reported oscillator signature findings. Therefore, if the encoding of time is responsible for the nonlinearity found in human tapping, the connectionist model would predict no effect of retention interval.

Although a goal of the broadcast theory is to explain how information about timing may be stored in memory, it does not directly address the role that short term memory might play when incorporated as a retention interval into a finger-tapping task. One possible prediction is that the oscillator signature may be more pronounced and shift to the left, when an ISI is held in memory. The longer the retention interval, the more variability or noise there may be, and subdivision of the time intervals might therefore occur at shorter ISI conditions. Another possible prediction, based on increasing amount of noise during the longer retention intervals, is that the benefit of subdividing decreases. With an increasing amount of noise in the memory representation of the ISI, there may no longer be an advantage of subdividing to minimize variance. This interpretation may predict a weaker oscillator signature that is highly variable.

If the oscillator signature is caused by 'natural' periods, where entrainable oscillators maintain some resistance, this theory may predict a relaxation toward a 'natural' rate while the ISI is held in memory. This may result in an exaggeration of the oscillator signature previously reported (Collyer et al., 1992; 1994; 1997). The longer the retention interval, that is, the further removed in time from the stimulus sounds, the more opportunity for the subject's representation of the ISI to gravitate or drift toward 'natural' time periods, producing a more pronounced oscillator signature.

Method

Subjects

Seven undergraduate students, five females and two males, attending the University of Rhode Island, volunteered to participate in this study. Each subject was paid $5 per hour for their participation and also received a $5 bonus when they completed all the sessions. All seven subjects followed through to completion and received the bonus.

Apparatus

The hardware used for collecting the data consisted of a Gateway 2000 486DX2 computer, a Sound Blaster 16 sound card, powered Radio Shack speakers, and a Casio rhythm generator. The software used for the presentation of stimuli, the timing of retention intervals, and the collection of responses was a MIDI music sequencer program, Cakewalk Professional, v 3.0. Additional software for converting and analyzing the data was the MF2T ("MIDI File to Text") file conversion program (van Oostrum, 1995) and the Microsoft Excel v 4.0 spreadsheet program and custom macro (Appendix A).

Design and Procedure

The experimental design was within-subjects; 2 Retention Intervals x 25 ISIs. Each subject participated in both conditions of the retention interval (5 and 25 seconds) for each of the 25 ISI conditions, ranging from 200 to 800 ms, in 25 ms steps. There was a total of 50 trials per session and each subject completed 3 replications of the session. For each of the sessions, the 50 combinations of retention interval and ISI were presented in a random order, with the subject unaware of the retention interval and ISI until they were already performing the task. The entire data set consisted of 1050 trials, 150 trials collected from each of the 7 subjects.

Data collection began during the fall semester of 1996 and was completed in the Spring of 1997. The average session lasted approximately 90 minutes and subjects performed only one session per week during daytime school hours at their convenience.

During the first session, each subject was introduced to the laboratory setting, signed an informed consent form, and read standardized instructions (Appendix B) for performing the task. The subject was seated at a table across from the experimenter at a computer terminal, with the Casio rhythm generator positioned so that they could comfortably tap on its key with the index finger of their dominant hand. They were also offered an arm rest if they preferred. At this time, they were given practice trials for both retention intervals at an ISI of 825 ms, to familiarize them with the experiment and ensure satisfactory understanding and performance of the task.

Each session consisted of 50 trials, with scheduled breaks after completing 15 trials and again after completing 20 more. The experimenter initiated the beginning of each trial by asking "Ready?" and the subject confirming. Each trial consisted of the subject first listening to the tempo of a series of 20 clearly audible (about 50dB SPL) beats at a specified ISI, and then cognitively rehearsing the tempo during the silent retention interval pause. Then, depending on the retention interval (5 or 25 seconds), the subject was signaled by a chime sound to begin tapping, attempting to reproduce the tempo previously heard. The subject continued to tap (approximately 30 taps) until a distinctive cymbal sound indicated the end of the trial.

Each trial was recorded using the Cakewalk software program and saved in MIDI format on a diskette. The MIDI files were converted to text format using the MF2T file conversion program (van Oostrum, 1995). The data from the text files, which consisted of event times for the subjects' first 28 taps after the retention interval, were then extracted and converted from beats/ticks to milliseconds with an EXCEL custom macro (Appendix A). From the 28 taps, the 'first difference' was taken, establishing the time in milliseconds between the taps, or what is referred to as the interresponse interval (IRI), which was the data of interest.

Results

The IRI as a function of ISI was examined for the 5 and 25 second retention intervals. The EXCEL custom macro was designed to calculate a median IRI value from the converted data for each of the 1050 trials, as well as other descriptive statistics for each trial, including the minimum IRI value[1], first quartile (Q1), third quartile (Q3), maximum IRI value[2], mean, standard deviation, and the semi-interquartile range (SIQR). An average (mean) of the three replications of the trial medians was taken at each ISI value for each subject under both retention intervals. A group mean IRI was then established for each ISI condition by averaging across all seven subjects.

The results of the two retention intervals are portrayed in Figure 4, where IRI is plotted as a percentage of ISI (IRI / ISI x 100). The graph represents two group oscillator signatures, one for the 5 second retention interval and the other at 25 seconds. The negative-going zero crossing for both retention intervals was found to be between 550 ms and 575 ms. In other words, subjects had a tendency to tap too slow at ISIs that were less than 550 ms and tapped too fast at ISIs longer than 575 ms, and this tendency was exhibited for both retention intervals. Interestingly, the negative-going zero crossings occurred at the same place for both retention intervals, agreeing closely with the longer of the two crossings observed in the previous oscillator signature findings (Collyer et al. 1992; 1994; 1997). Both conditions of the retention interval data are shown along with the data from Collyer et al. (1997) in Figure 5. Considering the data from 1997 as a zero retention interval, a pattern of nonlinearity emerges of increasing bias as the retention interval increases.

In order to establish whether the two retention intervals differed significantly from one another, multiple dependent t-tests were performed comparing retention intervals at each ISI condition, using the IRI as a percentage of ISI. Significant differences were found for three of the first twelve ISI conditions, prior to the negative-going zero crossing, where the largest discrepancy between the retention intervals appears visually. At an ISI of 250 ms, t (1,6) = 3.2, $p<.05$, subjects were tapping significantly slower when the ISI was held in memory for 25 seconds than for the retention interval of 5 seconds. Significant differences were also found for an ISI of 325 ms, t (1,6) = 2.9, $p<.05$, and for 400 ms, t (1,6) = 3.2, $p<.05$, again indicating that for the 25 second retention interval, subjects were tapping significantly slower than for the 5 second retention interval. Prior to the negative-going zero crossing, there appears to be a significant difference between the two retention intervals. The first twelve ISI conditions, ranging from 200 to 475 ms, represent a pattern of increased bias as ISI was held longer in memory, producing a clear distinction between the retention interval conditions. A significant difference between the retention intervals was also found at an ISI of 800 ms, t (1,6) = 2.90, $p<.05$, with subjects tapping significantly faster for the 25 second retention interval than for the 5 second retention interval. This difference in retention intervals is compatible with the idea of more pronounced bias at the 25s retention interval.

The retention interval conditions were also compared using a simple regression approach. For both retention intervals, a simple regression analysis was performed on the averaged oscillator signature and a 95% confidence interval was calculated. Although a linear line was fit to the data, there is no strong claim that residual bias of the two retention intervals represent linear functions. This approach was used only as a statistical method to see if the retention intervals were significantly different from one another. The confidence interval analysis for the 5s retention interval (SE = 1.33) is represented in Figure 6, along with the data points from the 25s retention interval. The analysis revealed that 8 out of the 25 ISIs from the 25s retention interval fall outside the 95% confidence interval of the 5s retention interval. When the regression analysis was performed and a 95% confidence interval was calculated on the average oscillator signature for the 25s retention interval (SE = 1.30), it was found that 9 of the 5s retention interval ISIs fall outside the 25s retention interval's 95% confidence interval. The results of the 25s retention interval analysis are represented in Figure 7, closely resembling a mirror-image of the 5s retention interval regression analysis. The two simple regression analyses (data Table C1 & C2 in Appendix C) confirm the findings of the dependent t-tests indicating that the retention intervals significantly differ from one another.

The semi-interquartile range was calculated (SIQR = Q3 - Q1 / 2), averaging across sessions and subjects, establishing a mean SIQR for each ISI condition. The SIQR, which is comparable to the standard deviation, was used as a measure of the variability of IRI and represents the precision of the subjects' performance for both retention intervals. Figure 8 shows a linear increase in variability for both retention intervals with a best fitting line drawn from a simple linear regression analysis. A dependent t-test, $t(1,24) = 2.25$, $p<.05$, found the 25 second retention interval condition ($M = 16.90$) to have an overall significantly larger SIQR than the 5 second condition ($M = 15.73$). The data indicate a linear increase of residual variability which is greater for the longer retention interval, but appears independent of the residual bias.

Subsequent analyses of within-trial drift in tapping rate were conducted in order to better understand the source of variability that makes up the bias function and where it comes from. The retention interval data provide two kinds of "drift" to consider: the "drift" that occurs during tapping and the "silent drift" that accumulates while the subject is cognitively rehearsing the tempo during the retention interval prior to tapping. The intercepts and slopes, calculated for a subset of the data, were used as indicators of the two types of drift. Of the 1050 individual trials, 250 trials were randomly selected for examination. An average intercept and an average slope were calculated at each ISI from the randomly selected individual trials for both retention interval conditions. It was presumed that this type of analysis may allow further interpretation of the residual bias that exists in the data -- with the intercept serving as an indicator of how much bias is already present at the beginning of tapping ("silent drift") and the slope representing the part of the bias that occurs after tapping begins.

The intercept data represent a part of the bias that, being independent of tap number in a trial, was not available from previous continuation tapping data. The bias present at the beginning of tapping may be seen as an indicator of the "silent drift" that accumulates during the retention interval and the possible effect that the retention interval had on the representation of ISI in memory. As shown in Figure 9, there appears to be tendency to begin tapping at a tempo too slow for the shorter ISIs and at a tempo too fast for the longer ISIs, with the 25 second retention interval more exaggerated prior to the negative-going zero crossing than the 5 second retention interval. The data indicate more "silent drift" from ISI occurring the longer the ISI is held in memory, providing more direct support for the influence of the retention interval.

The slopes of the selected trials were also examined in order to establish the extent to which drift during tapping contributes to the bias. Based on the outcome of the present data set, if drift during tapping accounts for the bias in the oscillator signatures, the direction of the slope for a given ISI would be different depending on which side of the negative-going zero crossing it was on. For example, a short ISI condition, prior to the negative-going zero crossing, should have a positive slope or a slowing down during tapping, whereas, the longer ISIs should have negative slopes or a speeding up as tapping continues during a trial. Figure 10 shows the averaged slopes for both retention intervals. It appears that for the longer ISI conditions, as indicated by negative slopes, there is a tendency to speed up during tapping. However, for the shorter ISIs, a consistent pattern of slowing down was not found.

Discussion

The findings presented here were the first to look at the role of short term memory in a finger-tapping task. The data indicate that memory, when incorporated into the previous method of investigation as a retention interval, affects the reproduction of tempo. The effect of retention interval on the oscillator signature gives rise to a number of theoretical considerations and offers insight into the source of the nonlinearity found in human tapping experiments.

The multiple oscillator connectionist model, which attributes the nonlinearity to the encoding phase, does not provide an obvious explanation for the memory findings. According to the model in its present form, if the encoding phases were the same for both retention intervals, both conditions should have produced oscillator signatures that were comparable and similar to the earlier findings. The data from the retention intervals suggests that memory does play a role in the nonlinearity produced. Memory may represent an alternative source of the nonlinearity found, in addition to the way intervals of time are represented or encoded. If further investigation into the memory component substantiates the present findings, a modification to include a parameter for memory would be appropriate.

The broadcast theory which proposes time intervals with relatively low variance could provide an explanation for a shift of the oscillator signature to shorter ISIs. As a tempo is held in memory, more noise or variability could accumulate resulting in a need to subdivide intervals sooner in order to reduce the variability. The data do not indicate a shift to the left relative to the previous oscillator signature finding (Collyer et al. 1992; 1994; 1997). The SIQR analysis indicated a linear increase of residual variability independent of residual bias which is in contrast to the expectation from the broadcast theory that there might be local decreases in variability. The alternative prediction from the theory, the notion that the benefit of subdividing an interval decreases as noise increases, enables the theory to account for increases in variability the longer an ISI is held in memory, but somewhat detracts from the theoretical reasoning from which it is based.

The remaining theory, which proposes internal timing mechanisms oscillating at 'natural' time periods in the system, may provide the best interpretation of the present findings. Underlying oscillators in this sub-second range, that have a degree of adjustibility, yet maintain some resistance when a tempo is held in memory, could provide a possible explanation for the source of the nonlinearity. The proposed prediction of a relaxation or gravitation towards a 'natural' rate, resulting in an exaggeration of the oscillator signature, is reasonably supported by the retention interval data. However, the 'natural' rate toward which memory regresses is represented by what would appear to be a single underlying oscillator between 550 and 575 ms. The retention interval data does not directly reflect the same wavelike oscillator signature pattern found in the previous research (Collyer et al. 1992; 1994; 1997), having two negative-going zero crossing regions. Instead, the retention interval data, with only one negative-going zero crossing, suggest a gravitation toward one 'natural' time period. It may be possible that the first negative-going zero crossing, present at the shorter ISIs in the previous data representing a zero retention interval, is associated only with synchronization. The cognitive "silent drift" that appears to continue as the retention interval increases represents a new source of variance to be considered. An experiment with synchronization, zero retention, and positive retention intervals, now needs to be performed. If the present pattern is found to be replicable, there may be a rationale for proposing a 'primary attractor' within this sub-second range. The 'primary attractor', if located roughly between 500 and 600 ms, can be seen in the oscillator signatures of the present memory data and the previously reported continuation tapping data.

While all three theories presented offer possible explanations for the oscillator signature findings, they are not equally successful in addressing the memory component. While the connectionist version of scalar timing theory provides a functional working model for how time intervals may be stored and retrieved in memory, and the broadcast theory offers a plausible way in which intervals may be neurologically processed within the memory system, they do not offer an explanation for why the retention intervals produce significant differences in the oscillator signature finding. The theory of 'natural' time periods is perhaps the most helpful for understanding and interpreting the outcome of the retention interval data. A 'natural' time period hypothesis would predict a gravitation toward a 'natural' rate of an internal free-running oscillator when an external stimulus is longer present to regulate synchronization.

The findings of this experiment are preliminary and further research is needed investigating the role that memory plays in human tapping. The retention interval effect introduces memory as an additional source of nonlinearity generating interesting questions that have yet to be theoretically considered. Additional analyses are possible on the retention interval data, as well as on data from the previous tapping experiments. An analysis of individual trials examining patterns in drift during tapping, comparing the intercepts and slopes from larger samples of data already collected, and possibly extrapolating back data points into the retention interval region of "silent drift", may all be informative. There is also a need for an experiment exploring range effects in order to formally rule out the possibility that the data represent a regression toward a mean rate of tapping.

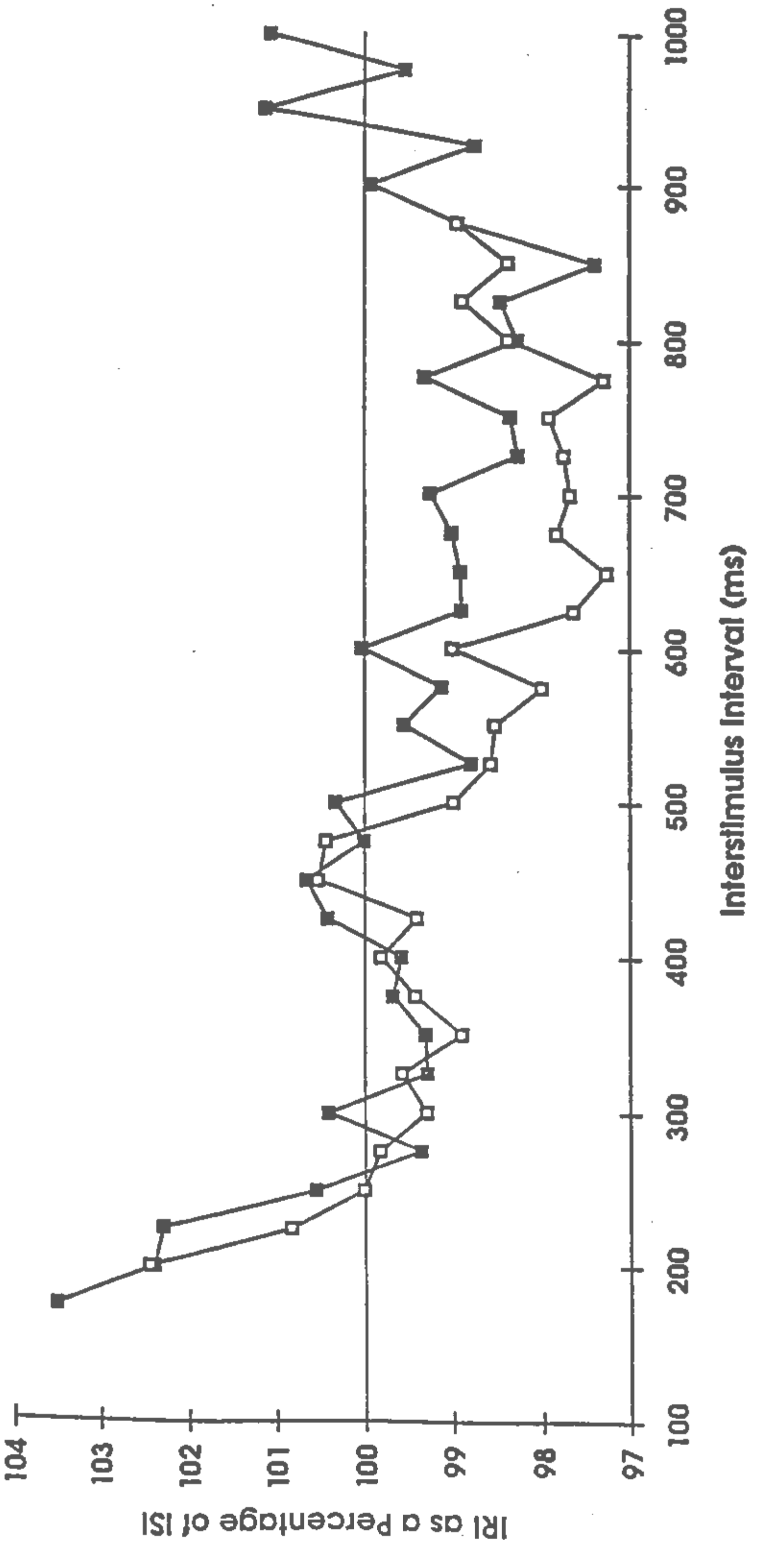
This study incorporated only two retention intervals and made use of the previous continuation tapping data as reference for a zero retention interval. There is a need for additional experimentation to include a zero retention interval condition, as well as different lengths of delay, using the same subjects. Investigations using rehearsal and/or distractor tasks during a retention interval, as well as new experiments exploring feedback for precision and accuracy may provide additional information to consider. Furthermore, the proposal of a 'primary attractor' within this sub-second range will hopefully motivate further experimentation on memory for temporal patterns and consideration of the theory of 'natural' time periods.

Footnotes

[1]The minimum IRI value served as an indicator for outliers which may have resulted either from double taps (bouncing the key during tapping) or from tapping too slow to the corresponding ISI so that 28 taps were not accomplished before the end of the trial. If a minimum IRI value was found to be <100 ms, or 0 ms, it was removed and the descriptive statistics were recalculated for the remaining taps in the trial.

[2]The maximum IRI value served as an indicator for missed taps, when the subject paused during tapping, then began again. If a maximum IRI value was more than twice the ISI condition, it was removed and the descriptive statistics were recalculated on the remaining taps in the trial. Approximately 0.3% of the taps were removed from the total data set, affecting less than 6% of the trials.

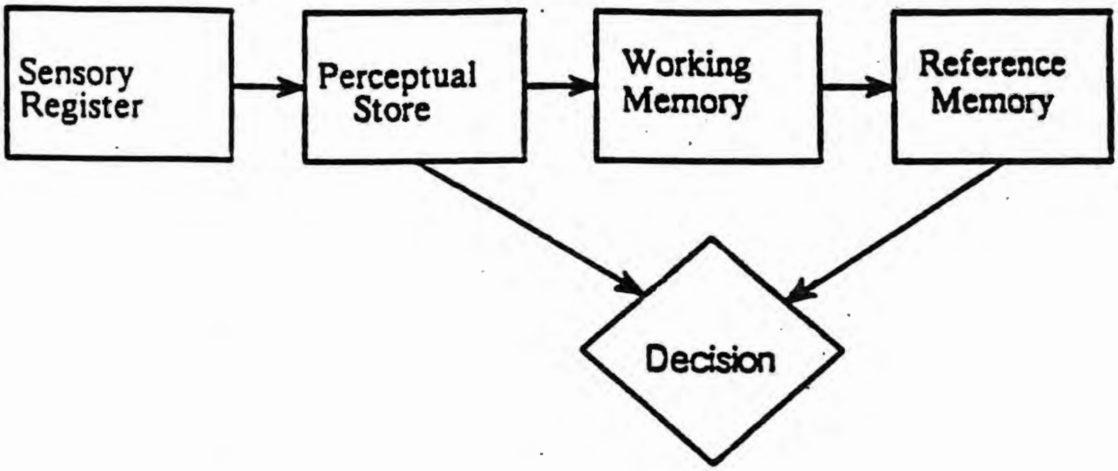
Figure 1. Two averaged oscillators signatures, one from a group of 16 subjects, with an ISI range of 200 to 875 ms (Collyer, Broadbent, & Church, 1994), and the other from 7 subjects with a range of 175 to 1000 ms (Collyer, Boatright-Horowitz & Hooper, 1997).



IRI as a Percentage of ISI
104
103
102
101
100
99
98
97
100
200
300
400
500
600
700
800
900
1000
Interstimulus Interval (ms)

Figure 2. A general information-processing model (top) and an information-processing model for timing (bottom). For the timing model, a decision to respond is based on a thresholded comparison between the number of pulses in the accumulator and the number of pulses in reference memory; the accumulator (*a*) is the product of the pacemaker rate (*lambda*) and physical time (*t*), and the reference memory (*r*) is the product of a memory constant (*k**) and the number of pulses in the accumulator at time of reinforcement. A response occurs when a measure of similarity (*s*), a ratio of the value in the accumulator and a value from reference memory, is below some threshold (Church & Broadbent, 1990).

A General Information–Processing Model



An Information–Processing Model for Timing

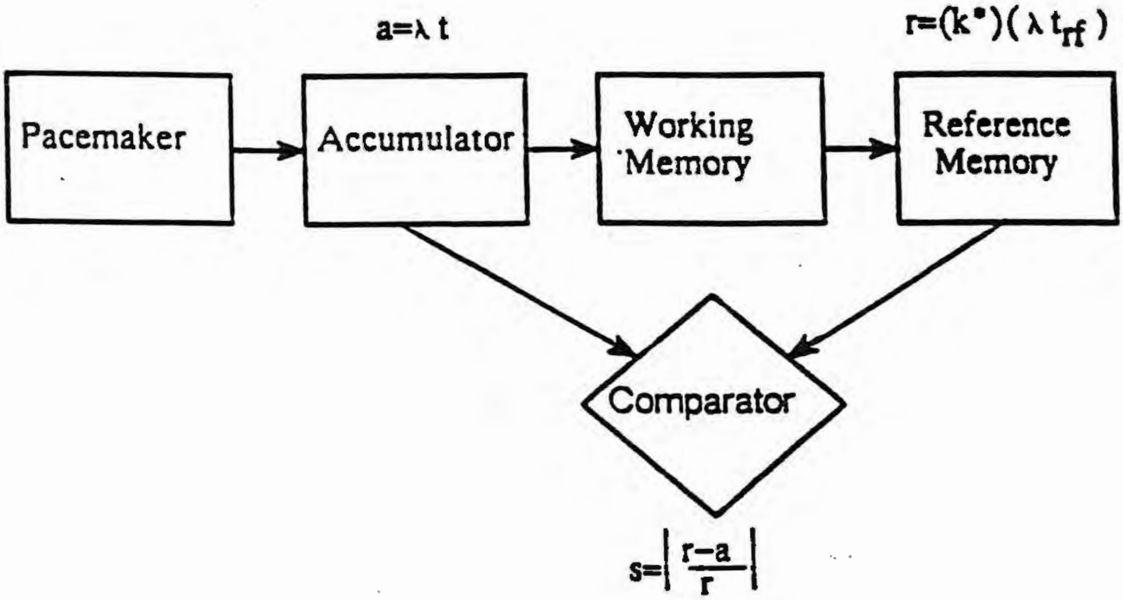
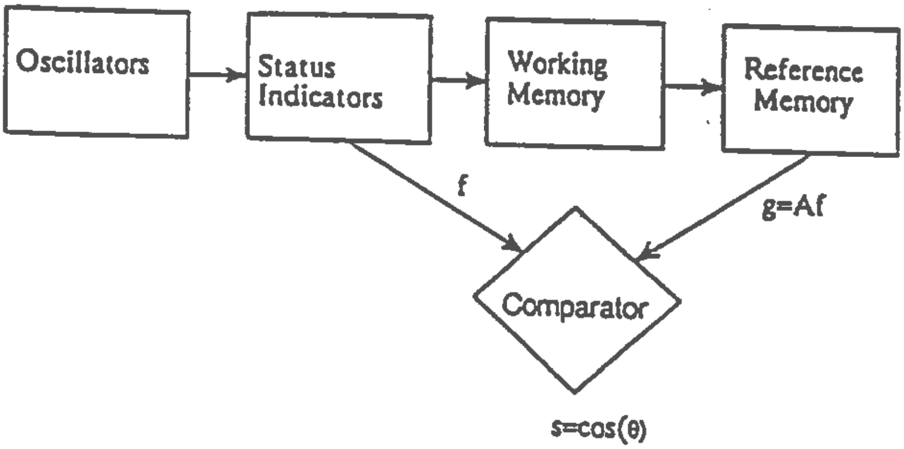


Figure 3. A connectionist model of timing in the familiar form (top) and a detailed version of the same model (bottom). The status indicators for storage (f_s) and retrieval (f_r) are vectors of 0s and 1s depending on the current half-phases of the oscillators. The working memory matrix (A_1) is the outer product of the storage vector and its transpose. The reference memory matrix (A) is a linear combination of weights from working memory and those presently in reference memory. A decision to respond is based on a thresholded comparison between a retrieval vector (f_r) and the output vector (g_r), which is the product of the reference memory matrix and the retrieval vector, with the cosine (s) as the measure of similarity (Church & Broadbent, 1990; 1991).


Oscillators
Status Indicators
Working Memory
Reference Memory
f
g=Af
Comparator
s=cos(θ)

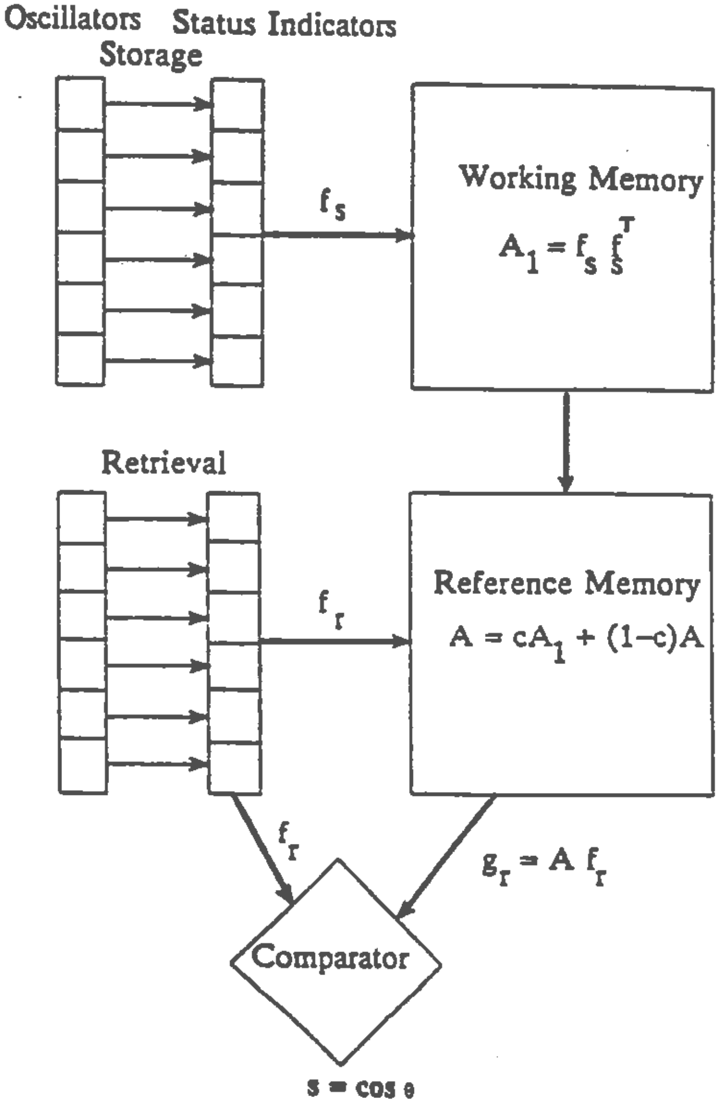

Oscillators
Status Indicators
Storage
Working Memory
f_s
$A_1 = f_s f_s^T$
Retrieval
Reference Memory
f_r
$A = cA_1 + (1-c)A$
f_r
$g_r = A f_r$
Comparator
s = cos θ

Figure 4. The averaged oscillator signatures from the retention interval data. The shaded data points show IRI as a percentage of ISI for the 5 second retention interval and the open data points represent the 25 second retention interval.

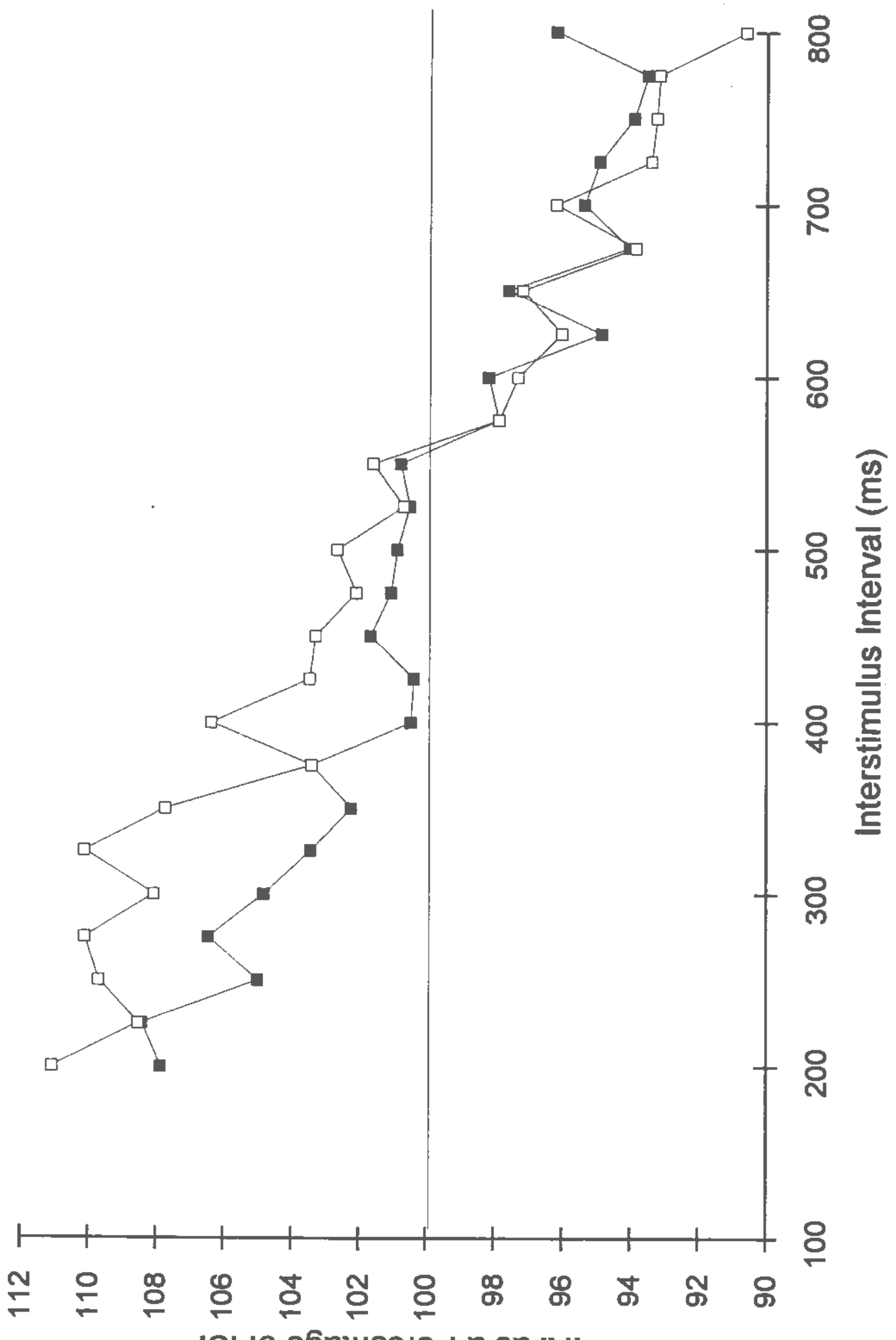

IRI as a Percentage of ISI
112
110
108
106
104
102
100
98
96
94
92
90
100
200
300
400
500
600
700
800
Interstimulus Interval (ms)

Figure 5. The oscillator signatures for the 5 second (shaded squares) and 25 second (open squares) retention intervals, and the previous oscillator signature (filled circles) from Collyer, Boatright-Horowitz & Hooper (1997) representing a zero retention interval. Notice that the three functions have a region of reduced bias just prior to the negative-going zero crossings.

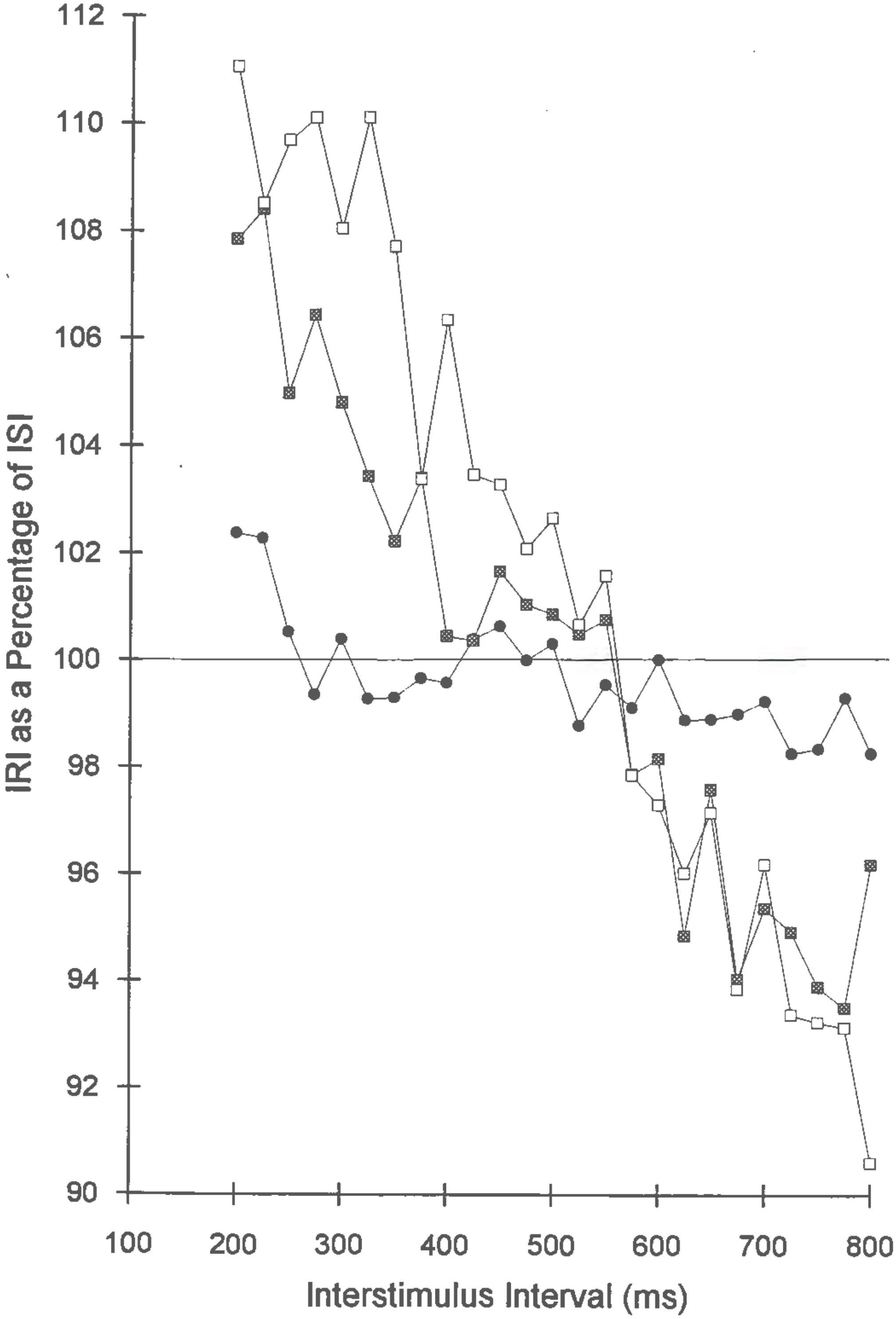

112
110
108
106
104
102
100
98
96
94
92
90
IRI as a Percentage of ISI
100
200
300
400
500
600
700
800
Interstimulus Interval (ms)

Figure 6. A regression line and 95% confidence interval for the 5s retention interval, with the 25s retention interval data points showing 8 of the 25 ISIs outside the confidence interval.

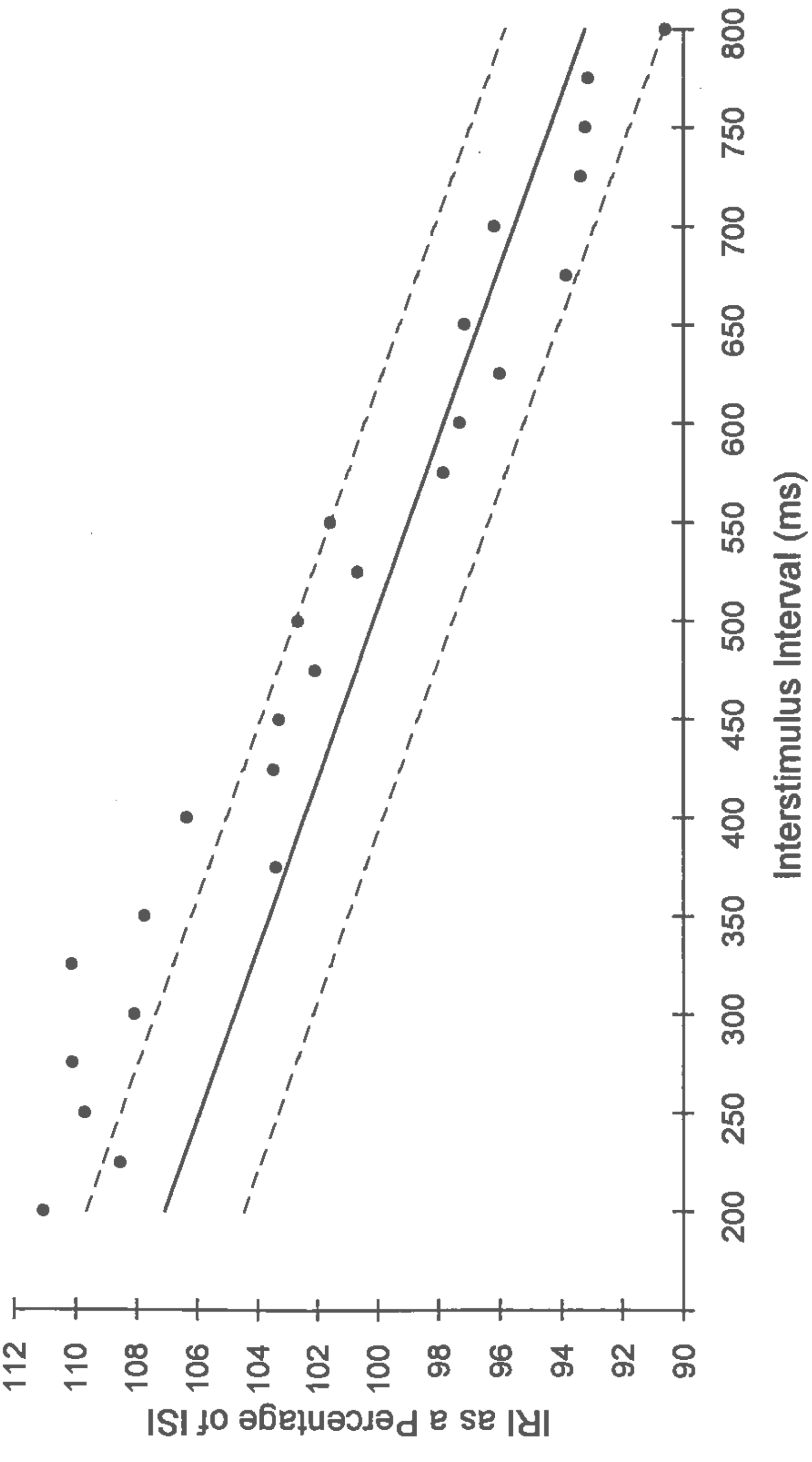

IRI as a Percentage of ISI
112
110
108
106
104
102
100
98
96
94
92
90
Interstimulus Interval (ms)
200
250
300
350
400
450
500
550
600
650
700
750
800

Figure 7. A regression line and 95% confidence interval for the 25s retention interval, showing 9 of the 25 ISIs from the 5s retention interval data outside the confidence interval.

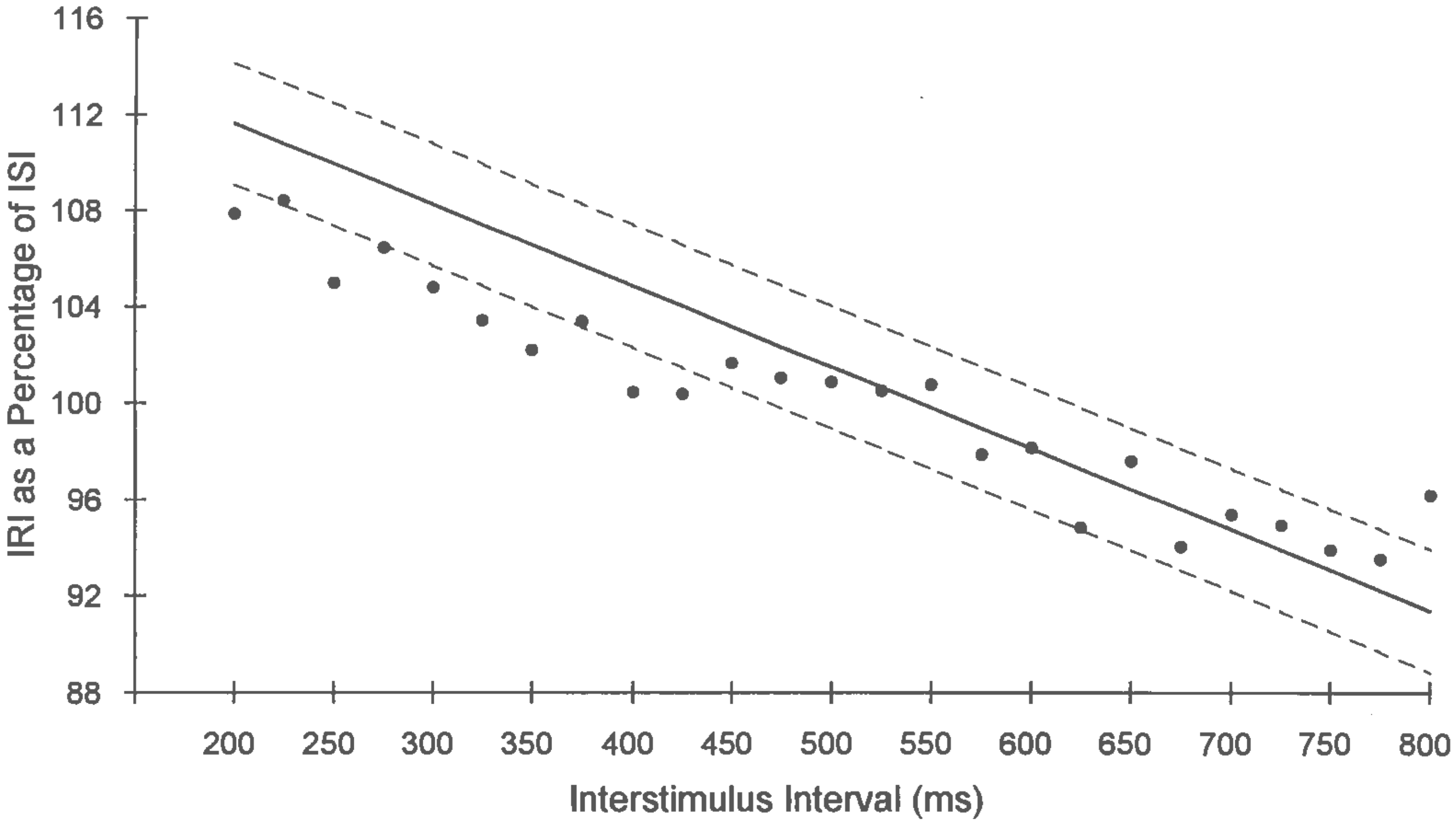

116
112
108
104
100
96
92
88
IRI as a Percentage of ISI
200
250
300
350
400
450
500
550
600
650
700
750
800
Interstimulus Interval (ms)

Figure 8. The semi-interquartile range (SIQR) as a function of ISI is shown for both retention intervals described by a linear function. The 5 second retention interval is plotted as shaded data points and the open data points represent the 25 second retention interval.

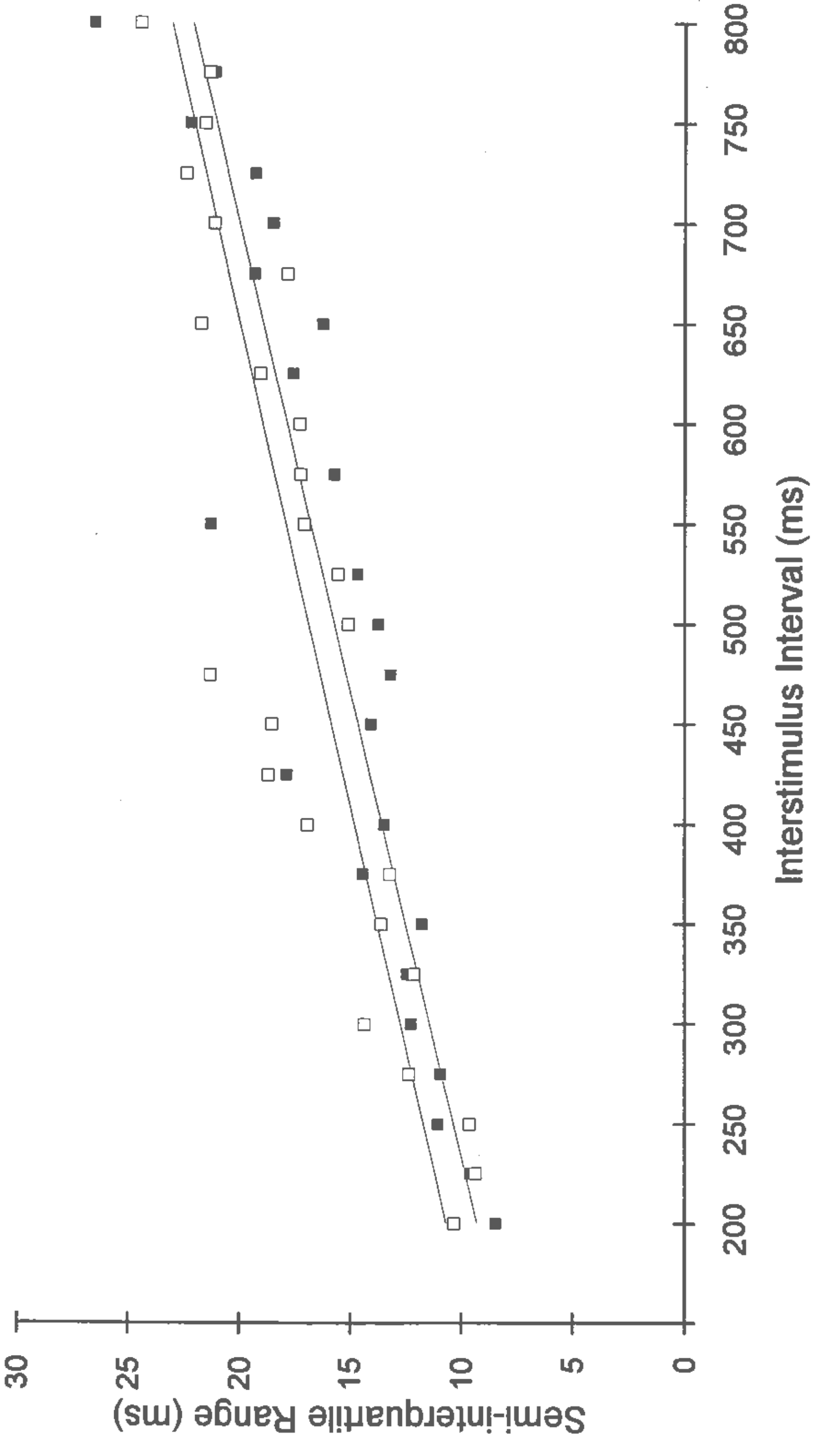

Semi-interquartile Range (ms)
Interstimulus Interval (ms)
0
5
10
15
20
25
30
200
250
300
350
400
450
500
550
600
650
700
750
800

Figure 9. The average intercept is shown as a percentage of ISI for both retention intervals. The top regression line is for the 25 second retention interval (open data points) and the bottom line is for the 5 second retention interval (shaded data points).

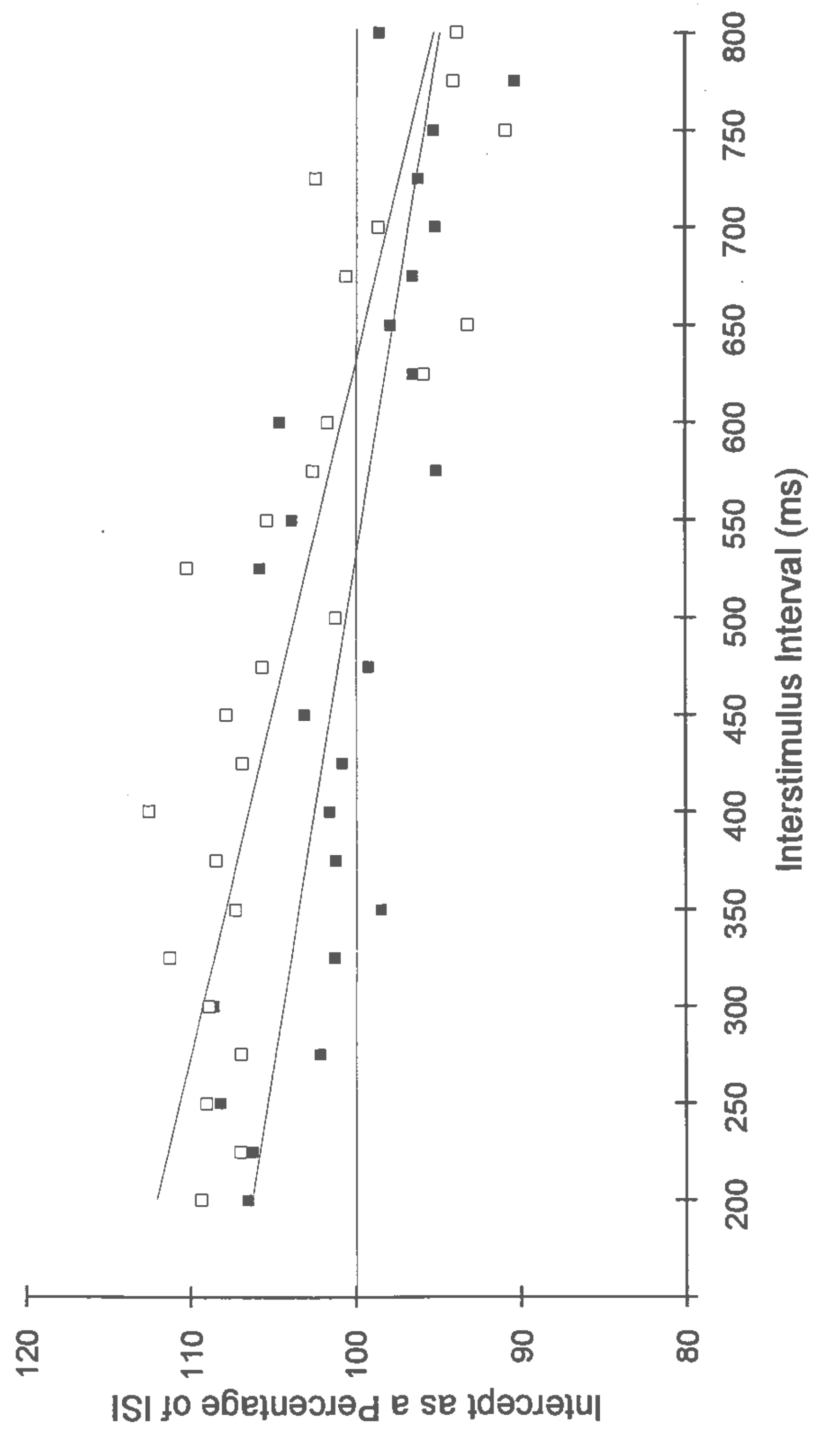
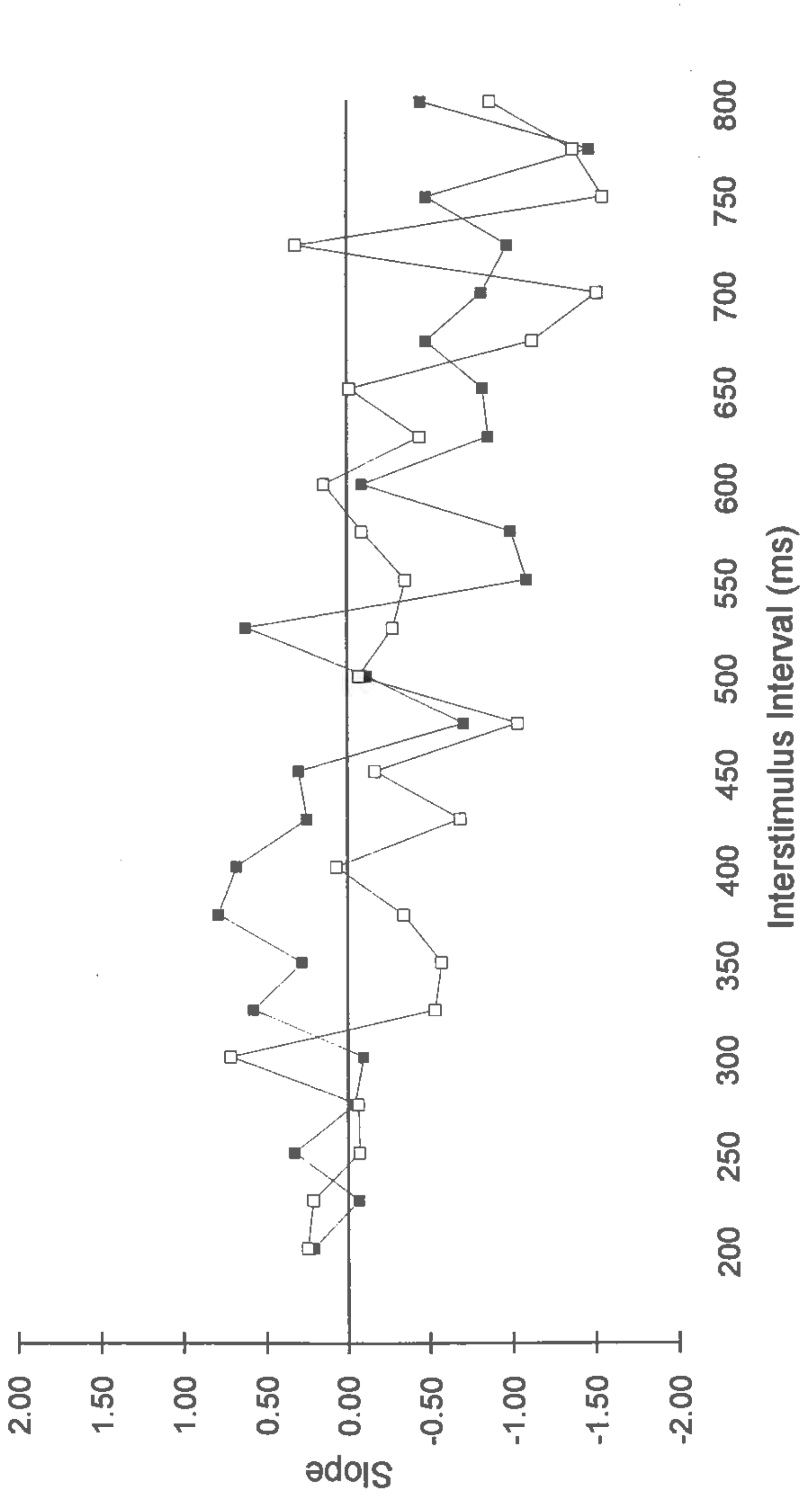

Intercept as a Percentage of ISI
120
110
100
90
80
Interstimulus Interval (ms)
200
250
300
350
400
450
500
550
600
650
700
750
800

Figure 10. The average slope at each ISI condition is plotted for both retention intervals. The slopes from the 5 second retention interval are shown as shaded data points and the open data points represent the slopes from the 25 second retention interval.


Slope
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
-2.00
200
250
300
350
400
450
500
550
600
650
700
750
800
Interstimulus Interval (ms)

Excel 4.0 Custom Macro

```
=WHILE(FORMULA.FIND("v=0",1,2,1,1,FALSE))
=EDIT.DELETE(2)
=NEXT()
=SELECT("C")
=RUN("FLATFILE.XLA!mco01.StubParse",FALSE)
=SELECT("R1C1")
=FORMULA.FIND("n=51")
=SELECT(OFFSET(ACTIVE.CELL(),1,-3))
=SELECT("R[0]C[0]:R[27]C[0]")
=COPY()
=SELECT("R2C7")
=PASTE.SPECIAL(3,1,FALSE,FALSE)
=SELECT("R[-1]C")
=CANCEL.COPY()
=FORMULA("Stamps")
=SELECT("R[2]C[1]")
=FORMULA("=RC[-1]-R[-1]C[-1]")
=SELECT("RC:R[26]C")
=FILL.DOWN()
=SELECT("R[-2]C[1]")
=FORMULA("IRI ms")
=SELECT("R[2]C")
=INPUT("ENTER THE CONDITION",1,,,,)
=IF(A26=200)
=FORMULA("=RC[-1]*.416667")
=END.IF()
=IF(A26=225)
=FORMULA("=RC[-1]*.46875")
=END.IF()
=IF(A26=250)
=FORMULA("=RC[-1]*.520833")
=END.IF()
=IF(A26=275)
=FORMULA("=RC[-1]*.572917")
=END.IF()
=IF(A26=300)
=FORMULA("=RC[-1]*.625")
=END.IF()
=IF(A26=325)
=FORMULA("=RC[-1]*.677083")
=END.IF()
=IF(A26=350)
=FORMULA("=RC[-1]*.729167")
=END.IF()
=IF(A26=375)
=FORMULA("=RC[-1]*.78125")
=END.IF()
```

```
=IF(A26=400)
=FORMULA("=RC[-1]*.833333")
=END.IF()
=IF(A26=425)
=FORMULA("=RC[-1]*.885417")
=END.IF()
=IF(A26=450)
=FORMULA("=RC[-1]*.9375")
=END.IF()
=IF(A26=475)
=FORMULA("=RC[-1]*.989583")
=END.IF()
=IF(A26=500)
=FORMULA("=RC[-1]*1.041667")
=END.IF()
=IF(A26=525)
=FORMULA("=RC[-1]*1.09375")
=END.IF()
=IF(A26=550)
=FORMULA("=RC[-1]*1.145833")
=END.IF()
=IF(A26=575)
=FORMULA("=RC[-1]*1.197917")
=END.IF()
=IF(A26=600)
=FORMULA("=RC[-1]*1.25")
=END.IF()
=IF(A26=625)
=FORMULA("=RC[-1]*1.302083")
=END.IF()
=IF(A26=650)
=FORMULA("=RC[-1]*1.354167")
=END.IF()
=IF(A26=675)
=FORMULA("=RC[-1]*1.40625")
=END.IF()
=IF(A26=700)
=FORMULA("=RC[-1]*1.458333")
=END.IF()
=IF(A26=725)
=FORMULA("=RC[-1]*1.510417")
=END.IF()
=IF(A26=750)
=FORMULA("=RC[-1]*1.5625")
=END.IF()
=IF(A26=775)
=FORMULA("=RC[-1]*1.614583")
=END.IF()
=IF(A26=800)
=FORMULA("=RC[-1]*1.666667")
```

```
=END.IF()
=SELECT("RC:R[26]C")
=FILL.DOWN()
=SELECT("C")
=FORMAT.NUMBER("0")
=SELECT("R[3]C[2]")
=FORMULA("Count")
=SELECT("RC[1]")
=FORMULA("=COUNT(R[-1]C[-3]:R[25]C[-3])")
=SELECT("R[1]C[-1]")
=FORMULA("Minimum")
=SELECT("RC[1]")
=FORMULA("=MIN(R[-2]C[-3]:R[24]C[-3])")
=SELECT("R[1]C[-1]")
=FORMULA("Q1")
=SELECT("RC[1]")
=FORMULA("=QUARTILE(R[-3]C[-3]:R[23]C[-3],1)")
=SELECT("R[1]C[-1]")
=FORMULA("Q2")
=SELECT("RC[1]")
=FORMULA("=QUARTILE(R[-4]C[-3]:R[22]C[-3],2)")
=SELECT("R[1]C[-1]")
=FORMULA("Q3")
=SELECT("RC[1]")
=FORMULA("=QUARTILE(R[-5]C[-3]:R[21]C[-3],3)")
=SELECT("R[1]C[-1]")
=FORMULA("Maximum")
=SELECT("RC[1]")
=FORMULA("=MAX(R[-6]C[-3]:R[20]C[-3])")
=SELECT("R[1]C[-1]")
=FORMULA("SIQR")
=SELECT("RC[1]")
=FORMULA("=(R[-2]C-R[-4]C)/2")
=SELECT("R[1]C[-1]")
=FORMULA("Mean")
=SELECT("RC[1]")
=FORMULA("=AVERAGE(R[-8]C[-3]:R[18]C[-3])")
=SELECT("R[1]C[-1]")
=FORMULA("StDev")
=SELECT("RC[1]")
=FORMULA("=STDEV(R[-9]C[-3]:R[17]C[-3])")
=SELECT("R3C11")
=SELECT("R[1]C[1]:R[9]C[1]")
=COPY()
=ACTIVATE("GSUM.XLS")
=PASTE.SPECIAL(3,1,FALSE,TRUE)
=SELECT("R[1]C")
=SAVE()
=RETURN()
```

Appendix B

Standardized Instructions

1) Using your dominant hand, find a comfortable position for your lower arm and wrist to rest so that you can tap your finger on the "Tom 2" key comfortably. Feel free to move the pad and the machine to find the best position for you.

2) You will first listen to a tempo, which consists of 20 equal interval beats. Then there will be a pause, depending on the trial, of either 5 or 25 seconds, during which you will cognitively rehearse the tempo. Then a chime will indicate when you should begin tapping. To the best of your ability attempt to reproduce the tempo you heard, tapping until a cymbal crash indicates the end of the trial.

3) During the pause, be sure not to be using any type of motor rehearsal, (tapping a foot, nodding your head); rehearse only in your mind.

4) We will do a sample trial first, to familiarize you with the experiment. During this time, feel free to ask any questions.

5) Any time you feel you need to take a break. Please let me know. Otherwise we will take two scheduled breaks, one after 15 trials and another after 35 trials.

Appendix C

Table C1

Simple Regression Approach for Comparison of the 5s Retention Interval

	95% Confidence Interval				
ISI	[	*Pred y*	]		25s RI
200	104.47	107.08	109.68	*	111.08
225	103.89	106.50	109.11		108.54
250	103.32	105.92	108.53	*	109.71
275	102.74	105.35	107.95	*	110.12
300	102.16	104.77	107.38	*	108.08
325	101.59	104.19	106.80	*	110.14
350	101.01	103.62	106.22	*	107.74
375	100.43	103.04	105.65		103.40
400	99.86	102.46	105.07	*	106.37
425	99.28	101.89	104.49		103.48
450	98.70	101.31	103.92		103.30
475	98.13	100.73	103.34		102.10
500	97.55	100.16	102.76		102.67
525	96.97	99.58	102.19		100.68
550	96.40	99.00	101.61		101.60
575	95.82	98.43	101.03		97.87
600	95.24	97.85	100.46		97.32
625	94.66	97.27	99.88		96.03
650	94.09	96.69	99.30		97.17
675	93.51	96.12	98.72		93.86
700	92.93	95.54	98.15		96.20
725	92.36	94.96	97.57		93.38
750	91.78	94.39	96.99		93.24
775	91.20	93.81	96.42		93.14
800	90.63	93.23	95.84	*	90.62

* indicates the 25s retention interval data points that fall outside the 95% confidence interval of the 5s retention interval regression line.

Table C2

Simple Regression Approach for Comparison of the 25s Retention Interval

	95% Confidence Interval				
ISI	[	*Pred y*	]		5s RI
200	109.10	111.64	114.19	*	107.87
225	108.25	110.80	113.35		108.43
250	107.41	109.96	112.50	*	104.99
275	106.56	109.11	111.66	*	106.46
300	105.72	108.27	110.82	*	104.82
325	104.88	107.42	109.97	*	103.45
350	104.03	106.58	109.13	*	102.23
375	103.19	105.74	108.28		103.42
400	102.34	104.89	107.44	*	100.47
425	101.50	104.05	106.60	*	100.38
450	100.65	103.20	105.75		101.68
475	99.81	102.36	104.91		101.06
500	98.97	101.51	104.06		100.87
525	98.12	100.67	103.22		100.51
550	97.28	99.83	102.37		100.78
575	96.43	98.98	101.53		97.88
600	95.59	98.14	100.69		98.17
625	94.75	97.29	99.84		94.85
650	93.90	96.45	99.00		97.60
675	93.06	95.61	98.15		94.05
700	92.21	94.76	97.31		95.38
725	91.37	93.92	96.47		94.93
750	90.53	93.07	95.62		93.90
775	89.68	92.23	94.78		93.51
800	88.84	91.38	93.93	*	96.20

* indicates the 5s retention interval data points that fall outside the 95% confidence interval of the 25s retention interval regression line.

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